Comment on the report "Observation of abundant heat production from a reactor device and of isotopic changes in the fuel" by Levi et al

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Abstract—**In a recent report [2] titled "Observation of abundant heat production from a reactor device and of isotopic changes in the fuel" and published by Bologna University, G. Levi and co-workers put forth several claims concerning the performance of the so-called E-Cat of inventor Andrea Rossi. High and sustained levels of anomalous heat production are reported in extended tests of a reactor device. These results are based on a calculated temperature of 1400C from infra-red camera thermography measurements that assumes gray-body radiation from an alumina surface. We show that when the varying spectral emissivity of alumina is taken into account the calculated temperature is much lower, and estimated power out matches power in to within the experimental error, so resolving this anomaly. Claimed isotopic shift results in the same report derive from material handled by the inventor, and therefore are not independent.**

Contents

I. Introduction

Extraordinary claims of excess heat observations from supposed low temperature nuclear reactions, or "cold fusion" have a long history from 1989 when Fleishmann and Pons made such claims. Much subsequent work has failed to confirm any results considered anomalous by the wider scientific community, and attempts to explain the results within understood nuclear physics have thus far proved unsuccessful, with major problems to be overcome and no coherent experimental support. For this reason it is now generally accepted by scientists that such low temperature nuclear reactions do not happen at the rate necessary to generate observable excess heat. Nevertheless a few scientists continue to conduct experiments in this area and claims of excess heat are common, although none have thus far proved both replicable and robustly beyond all possible experimental error.

This fringe area of science has recently been energized by an inventor, Andrea Rossi, (hereafter called Rossi) who claims to have made devices that generate high levels of excess heat. These claims, if true, would be easily testable beyond experimental error and of extraordinary interest to both science, as some effect requiring a better understanding of the interactions between nuclear and solid-state physics, and industry, as a cheap and portable source of energy. Needless to say, thus far most consider these claims incorrect.

Rossi has made a number of demonstrations of his devices that apparently show excess energy and have created some interest in the blogosphere. Also, more significantly, he has organized tests which are claimed independent, by academics at Bologna and Uppsala Universities. Tests conducted have results in reports [1], [2] that claim extraordinary levels of excess heat generated over a significant time.

These tests have been conducted in a manner that is not completely independent, with the involvement of Rossi in some of the testing. Nevertheless the fact that academics have made the test [2] in a separate lab, and the extraordinary nature of the results, has significance beyond the blogosphere and sparked significant industrial [3] and governmental [4] interest.

The two reports on Rossi devices written by academics thus deserve scrutiny. The first report [1] was published on Arxiv in 2013 has been scrutinized by others [6], who identify a number of potential issues that would require further investigation before the results could be considered safe. The authors themselves view these results as indicative, to be settled by the second report. The second report [2], published by Bologna University in 2014, has the stated intention of redoing the original results with improved methodology and over a period of time that makes the anomaly impossible to explain through any chemical mechanism. The claims of excess heat in this second report [2], hereafter referred to as the Report, are the subject of this comment.

The next Section details related work, Section III introduces the tests conducted in the Report, and Section IV contains the main thermography re-analysis. The next section uses this to recalculate the estimated power from the reactor device. Section VI discusses a number of additional issues that may affect results. Section VII briefly considers the isotopic shift results. Finally Section VIII concludes and Section IX notes the reaction to this document. The code used to generate the recalculated temperature and power values is included as Appendix A.

II. Related Work

[5] details the significance of spectral emissivity in the Report measurements, and notes the key mistake made of conflating band emissivity and spectral emissivity. We follow this work for the detailed emissivity figures used here to generate results, its recognition of band emissivity as important in determining temperature. However in calculating the required temperature adjustment [5] implicitly assumes that grey body band radiance varies with temperature as does grey body total radiance. From this [5] calculates lower temperatures in this test that nevertheless show significant excess heat. In this paper we calculate a more accurate and markedly different solution based on numerical integration of the Planck Law.

[7] concludes that the correct temperature for the tests in the Report is much lower than stated, but they do not give their calculations, nor precisely calculate power out based on the new temperature.

[8] describes some experimental investigation of alumina tube thermal characteristics, which confirm that the Rossi device temperature would be higher than calculated by the report [2] for the claimed dissipated power.

In [9] a USPTO examiner rejects a patent application from Rossi on the grounds that the data from the Report was unsafe evidence of correct operation of Rossi's device. A number of grounds were given, those relevant to the work here are that there was no control, and the results rely on emissivity values from textbooks when the real emissivity of alumina is known to be variable.

There remains an interesting question, which this paper addresses: given the data from the Report and *correct* calculations what is the likely performance of the Rossi device? The expectation would be near zero excess heat, and therefore so-called COP (coefficient of output power) equal to 1 where:

$$\mathrm{COP} = \frac{\text{Total energy out}}{\text{Total energy in}}$$

Note that chemical energy released or absorbed during the test might make COP differ from 1 but in this case the small mass of the tested material and long duration of the test makes such deviation from expectation very small.

III. Test Methodology

The Report details the device to be tested as a small alumina tube "reactor" heated electrically via embedded heater wires made of Inconel. Measured electrical power heats the reactor via a feedback loop using a thermocouple embedded in the tube. The total heating power used during tests ranges from a few 100W to 900W. As a result the reactor becomes hot with temperatures of up to 1400C claimed.

The claims of "abundant" excess heat in the Report rest on the difference between dissipated heat from the reactor, estimated as the sum of calculated radiant and convective losses, and the measured electrical power in. The small size of the reactor and long period of the tests makes any chemical contribution to the claimed excess negligible. The results are thus indeed extraordinary providing that the input power measurement, and the output power calculation, are safe.

In order to calculate output power the reactor surface is monitored by an infra-red thermographic camera and surface temperature calculated from infra-red radiance. Power dissipated by radiation and convection is then calculated from theoretical parameters.

Surprisingly there is no independent check of this indirect temperature measurement method. This lack is explained in the Report as due to a mechanical difficulty in attaching thermocouples to the reactor surface. The embedded temperature measurement device in the reactor core was provided by the inventor Rossi and not used other than to stabilise reactor temperature in a feedback loop using equipment provided for the Report authors by Rossi and treated by them as a black box.

The reactor was tested initially without "fuel", where the calculated output power is expected to match the input electrical power of approximately 450W. The observed approximate match was cited in the Report as validation for the indirect thermography and power calculations. The extraordinary results come from subsequent tests of the same reactor with "fuel" and input powers of approximately 750W and 850W, resulting in calculated output powers of approximately 2400W and 3300W respectively.

It is notable that, as the authors of the Report themselves point out, there is no control. Instead the no "fuel" so-called "dummy" test is conducted at a much lower input power. The fact that the claimed temperatures are much higher than the initial temperature makes reliance on calculations that match at the much lower temperature unsafe, contrary to what is suggested in the Report. Additional effects at higher temperatures negligible at lower temperature may invalidate results, and we will explore this in the next two sections.

The authors of the report note, as additional evidence for excess heat, the fact that their calculated output power varies by 700W [2]:

> What immediately stands out in Table 7 is the sharp difference between values obtained in the first ten days of the test (files 1 to 5 included), when power input to the reactor was kept at lower levels, and those obtained in the second period, in which power supply was increased by slightly more than 100 W. The effect of raising power input was an increase in power emission of about 700 W.

Thus even if calculations of output power have errors one might expect these errors to be relatively constant in the 750W and 850W input cases, and this acceleration in calculated output is a significant anomalous factor. If these results stand they are indeed anomalous, even without the safety and assurance of a control.

In addition to the experiment, samples of the reactor "fuel" and "ash" were taken for analysis, with unusual isotopic shift results, showing particularly a change in nickel from natural isotopic abundance (approximately 30% ^{62}Ni) to 99% pure ^{62}Ni.

IV. Thermography

Infra-red cameras are an established non-contact way to measure surface temperature. The camera measures radiant power within a given optical bandwidth, in this case the instrument chosen was the Optris PI-160. This [10] has an optical system with sensitivity over the band 7.5μm - 13μm.

The PI-160 instrument is used by entering an emissivity value for the surface to be measured. Each pixel of the camera receives radiant power that is converted by the camera software into a temperature using the relevant gray-body radiation curve. This relies on a known correct value for surface emissivity.

The Report notes that alumina is not a gray body, and addresses this problem by using temperature-dependent values for alumina total emissivity found in a reference. Linearly interpolation from the given values makes a continuous curve for emissivity. This curve is used as follows:

1) Set ϵ_{est} to 1.0
2) Input ϵ_{est} to PI-160 as emissivity
3) Set T_{est} to the temperature reading from the PI-160.
4) Set ϵ_{est} from the interpolated curve to the value corresponding to T_{est}.
5) If ϵ_{est} has changed go to Step 2.

This method will normally converge quickly and lead to the correct value of temperature if the curve for emissivity versus temperature is correct. The emissivity needed for this curve is that seen by the Optris instrument in the sensor band of 7.5µm to 13µm, and hereafter called *band emissivity*. For many materials, including ideal gray bodies, the *band emissivity* and *total emissivity* are the same. However for others the two values are different.

The mistake in the Report comes from using textbook values for total emissivity when what is needed is the corresponding value of the band emissivity. Alumina is well known to have a spectral emissivity that varies markedly over the range of interest. The emissivity over the Optris band varies between 0.85 and 0.95 and is well approximated by 0.9. The emissivity at higher frequencies is much lower, and this leads to a total emissivity as noted in [2] that decreases with increasing temperature down to a much lower value of 0.4.

The test leading to claimed high excess heat was conducted at a reported temperature of 1392C-1412C. Following the total emissivity curve the emissivity value at these temperatures is 0.4. The correct value is however the band emissivity of 0.9.

In order to determine the actual measured temperature for these measurements we need to understand how the radiance in the band $\lambda_0 = 7.5$µm to $\lambda_1 = 13$µm is combined in the Optris camera with the entered emissivity to calculate temperature. The radiance sensed by the PI-160 from an ideal gray body of emissivity ϵ and temperature T is given from the Planck Law and the Optris sensor band sensitivity $B(\lambda)$ and hereafter called the *band signal*. We follow [5] by integrating over the sensor bandwidth from $\lambda 0$ to $\lambda 1$:

$$R(\epsilon, T) = K \int_{\lambda_0}^{\lambda_1} B(\lambda) \frac{hc}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} d\lambda \qquad (1)$$

Here K is a constant that will cancel in what follows. Note that although the exact sensor band sensitivity $B(\lambda)$ is not known the typical sensitivity for such sensors, which is used here following [5], will suffice since the results are not very dependent on variation in sensitivity over the band.

The significant difference between the results here and those given in [5] comes from Equation 1. In [5] the dependence of R on T is assumed to be:

$$R \propto T^4$$

That would be true were the integral over the entire wavelength range, in which case the well known black body power temperature dependence would apply. However the integral is over the range $\lambda_0 - \lambda_1$ of the Optris sensor which is at a wavelength much larger than the black body radiation peak at the temperatures of interest here. This makes the dependence of R on T close to that of the Rayleigh-Jeans Law, for which $R \propto T$. The recalculation here will use a numerical integration of Equation 1 for an accurate solution. This approximate analysis shows that compared with [5] the exponent of T will be approximately 1, rather than 4, and that therefore the actual temperature adjustment to the Report values will be larger than is calculated in [5].

The correct temperature T_{real} relates to that given in the Report by equating band signal calculated from the Report value of emissivity ϵ_{rep}, and calculated temperature T_{rep}, to that from the band emissivity ϵ_{band} and temperature T_{real}:

$$R(\epsilon_{rep}, T_{rep}) = R(\epsilon_{band}, T_{real})$$

Using the above equation, and the dependence of ϵ_{rep} on T_{rep} defined by alumina total emissivity and used in the Report, we define a compensation function:

$$T_{real} = T_{adj}(T_{rep})$$

Calculating this function requires numerical integration as in Equation 1. Table I shows the numerically computed values of T_{real} versus T_{rep} for two typical files of data in the Report.

File number	Report Temperature T_{rep}	Real Temperature $T_{real} = T_{adj}(T_{rep})$
3	1256	713
12	1401	779

TABLE I
RECALCULATED TEMPERATURES FROM REPORT TESTS

These results depend slightly on the Optris bolometer spectral sensitivity $B(\lambda)$ which is not precisely known, this must be considered an additional experimental error that is not considered by the Report.

V. Power Estimation

The Report calculates total dissipated power as a sum of radiated and convected components. Both are dependent on temperature. Following the Stephan Boltzmann Law radiated power is calculated as:

$$C_r A \epsilon_{tot} T^4$$

where C is a constant, A is the surface area, and T is the radiating surface temperature. The constants do not matter for calculation of the ratio of real to Report-calculated radiated powers:

$$\frac{Prad_{real}}{Prad_{rep}} = \frac{\epsilon_{tot}(T_{real})}{\epsilon_{tot}(T_{rep})} \frac{T_{real}^4}{T_{rep}^4}$$

Here $\epsilon_{tot}(T)$ is the temperature-dependent total emissivity of alumina. This is estimated in the Report from data in a materials reference. We accept here the given values for ϵ_{tot} with the proviso that the actual emissivity of alumina is known to be dependent on crystalline microstructure and surface treatment and therefore these values are approximate.

Convective power is calculated in the Report as (for small changes) proportional to $T^{1.25}$:

$$C_{conv} T^{1.25}$$

where C_{conv} is a constant that will cancel and therefore:

$$\frac{Pconv_{real}}{Pconv_{rep}} = \frac{T_{real}^{1.25}}{T_{rep}^{1.25}}$$

Applying these adjustments to the Report data we have the results shown in Table II. It should be noted that these results are approximate and a more careful calculation would require detailed data not provided in the report.

Data file number	Input Power	Report Output Power	Report COP	Real Output Power	Real COP
3	755	2418	3.20	808	1.07
12	865	3179	3.67	921	1.064

TABLE II
RECALCULATED POWERS FROM TESTS

What is most striking about these recalculated results is that the apparent nonlinear increase in output with input noted by the Report authors has vanished. The two high temperature tests show calculated output powers a constant ratio of the input power, as expected given that the various error mechanisms do not change significantly over such a small temperature change.

Why then did the original Report calculation lead to apparent nonlinearity? The answer comes from the way that total power and total band radiance vary with temperature. Band radiance (for a band, 7.5µm to 13 µm, at much longer wavelength than the black body radiation peak spectral radiance at 3µm) varies as T^n where $n \ll 4$ whereas total power varies as T^4. The difference results in the correction required to the report calculations for power, and is highly nonlinear with input power.

The new calculations shown here precisely correct the apparently nonlinear relationship between input and output power shown in the Report.

VI. Caveats

The calculations here show that the tests described in the Report do not represent evidence of anomalous excess heat production. The new calculations follow as far as possible the methods of the Report, correcting the error deriving from conflation of band emissivity and total emissivity.

There are a number of additional sources of uncertainty in these calculations, not considered in the Report, that would need to be considered in any future application of this methodology. We consider these below.

A. Emissivity Errors

The reactor surface used here has ridges. These, when compared with a flat surface, will provide some reflection of radiated energy and therefore increase emissivity according to the *view factor*. This correction has a view factor (configuration factor) F, that for regular 90° apex ridges as here is known [11] to be:

$$F = 1 - \sin 45^\circ = 0.293$$

The total radiation is the sum of direct, singly reflected, multiply reflected, etc. The nth reflection contributes $\epsilon((1-\epsilon)F)^n$ to the total from which we deduce the effective emissivity ϵ' of a surface with view factor F to be:

$$\epsilon' = \epsilon \sum_{n=0}^{\infty} (F(1-\epsilon))^n = \frac{\epsilon}{1 - F(1-\epsilon)}$$

Table III shows this relationship tabulated. The effect on the calculations here is small because the changes in alumina band emissivity and total emissivity affect the calculated radiated power P_{rad} in opposite directions.

ϵ	ϵ'	P'_{rad}/P_{rad}
0.4	0.485	$+21\%$
0.9	0.927	-5%

TABLE III
CORRECTION DUE TO VIEW FACTOR

This correction to ϵ is well understood and deterministic, therefore it is included in the recalculations here made in the previous sections.

In addition to this error the spectral emissivity of alumina at higher frequencies is highly dependent on surface porosity and crystalline micro-structure, therefore the values used here (following [5]) may not reflect the actual experiment. This error is perhaps the most significant since no interpretation can be made of output power without the spectral emissivity of the precise alumina used in this test.

B. Translucency errors

Alumina is known to be translucent at lower wavelengths. This cannot be described as a different emissivity and has an effect on the results which is uncertain although probably positive for measured COP. [12] shows that when alumina is transparent its measured emissivity depends on how it is heated: in this case the hot heater wires close to the alumina surface may radiate at an effective emissivity different from the alumina. This error is impossible to quantify because it depends on the heater wire emissivity, temperature, and surface coverage, all of which are unknown.

Data File	Approx Temperature (C)	resistivity ($\mu\Omega$m)	Joule Heating Power (W)	Total power (W)	Ratio	Ratio normalized
Dummy	360	1.09	6.7	486	0.01379	1.000
3	713	1.13	36.49	791.48	0.04610	3.343
5	705	1.13	36.13	785.79	0.04598	3.334
13	775	1.13	41.62	910.47	0.04571	3.314
15	779	1.13	41.46	905	0.05481	3.322

TABLE IV
COMPARISON OF JOULE HEATING AND TOTAL INPUT POWERS

C. Electrical Errors

This comment has not attempted to address all other errors that might exist in the output or input power calculations. In addition to the issues noted here that result in significant uncertainty not considered in [2], insufficient information is presented to know whether the error analysis from the authors of [2] is complete.

Nevertheless there is much information available in the Report about the electrical measurements used, and from this one significant source of error can be determined.

The input power is supplied from three-phase mains. Power is measured using a PCE-830 three phase power analyzer and some care is taken to check that any harmonics present in the measured signals are captured by the analyzer. The exact way that input power is measured is not clarified, but usually the total power from the PCE-830, the sum of the power from each phase, would be taken.

The PCE-830 measures power by true integration of voltage and current on each of the three phases. This method is normally accurate and allows the true power delivered to the load to be correctly estimated. Accuracy of measurement is related to accuracy of current and voltage measurement and must be determined from the manufacturer's specification.

The Report describes in detail a Delta connection of the device to the three phase supply supply. The reported data gives so called *Joule heating powers*, the power dissipated in connecting leads, and supply powers for all tests. From the connection diagram the ratio between these two powers must be fixed and related to the ratio between the resistances of the Inconel heating coils and the connection wire. This cannot change from one test to another. The electrical powers for dummy and active tests are shown in Table IV. The normalized ratio would be expected to be near 1 to within measurement accuracy, because it depends only on the ratio of heater and connection wire resistance. A possible deviation from this would be due to the variation in Inconel wire resistivity with temperature which is much too small over the given range [13] to account for the factor of 3.3 difference between dummy and active data.

This difference might be related to some change in the connection of the device between active and dummy tests. That would not in itself invalidate the results, since the power measurement from the PCE-830 is true power and the "Joule heating" correction is very small, so if this is wrong it is a small error.

However some caution must be exercised because the authors show in their report a typical current waveform with a very high crest factor - close to 4. Such high crest factors may lead to additional errors in current and therefore power measurement - they are outside the instrument specification [14] for accurate power measurement.

Summary: The given electrical data shows a clear anomaly that indicates a change in electrical measurements between dummy and active tests. A comparison of the stated information with the PCE-830 specifications shows that the electrical power measurement could have significant error due to high crest factor in the measured waveforms, if so a change in measured currents between dummy and active tests due to change in electrical connections (e.g. Wye to Delta connection) could lead to a difference between dummy and active COP estimates due to such measurement error, as well as errors in each separately. There is insufficient information to evaluate this error.

D. Remarks

The view factor correction noted in section VI-A has been included in the results here which otherwise follow as far as possible the methodology of the Report. This correction increases COP values by approximately 15%, so that omitting it would lead to COP < 1. There may be other small corrections not considered here. The calculation of total power out is particularly complex and the values from the report for convection may perhaps contain other errors, due to assumptions made in the theoretical analysis in which equations for ideal geometry are used without consideration of edge effects. Against this it should be noted that convection is a relatively small amount of the active test output power, which is dominated by radiation.

In such a situation much greater confidence could be given to the analysis were results from a control experiment presented in which the same input power was used but without the active material thought to generate excess heat. The Report gives as reason for this lack that the high temperatures might damage the heater element. The actual temperature in this test is much lower than calculated in the Report and therefore a control test would presumably be possible without danger to the equipment, even if the concerns of the Report were correct.

VII. Isotopic Shifts

Isotopic tests of a sample of the fuel and ash show normal isotopic abundance for the fuel, and a striking 99% ^{62}Ni abundance in the ash. Both insertion and removal of this material from the reactor are stated in the report as being handled by the device inventor Rossi. The Report states that at least one of the authors was present during this process. This does not make these results independent because there could be no independent check that both operations were performed correctly without substitution.

The Report suggests that the measured isotopic shift is extraordinary and shows nuclear conversion. Isotopic shift can occur without nuclear conversion through various natural mechanisms that perform isotope enrichment. A particularly striking example of this is in the mercury found in old CFL bulbs, where the mechanism appears to be an unusual fractionation process described by Mead [15]. However in this example, and others, the fractionation is never complete. The results here of approximately 20% ^{62}Ni enriched to 99% within one step, also the fact that a random sample of the "ash" is so enriched would appear to imply that all of the "fuel" Ni has been isotopically converted, given a closed system, are extraordinary.

While speculation as to the meaning of this isotopic shift measurement is beyond the scope of this report there is one consequence that can properly be considered. We assume in what follows that the 99% measurement is considered accurate for the bulk sample. This is the simplest hypothesis, and is implicitly followed in the Report. Should the measurement not be accurate for the bulk of the fuel there would no longer be clear evidence of nuclear transmutation. Some new and remarkably effective fractionation mechanism could be hypothesised with the experimental and theoretical difficulties from nuclear transformation.

Supposing the measurement accurate, the ^{62}Ni isotopic shift is doubly extraordinary. It cannot be explained even by an extraordinary LENR hypothesis such as neutron formation from protons and subsequent capture by the ^{58}Ni. For such a conversion to happen, whatever the intermediate pathways, the overall result would be:

$$4^1\mathrm{H} + ^{58}\mathrm{Ni} \longrightarrow ^{62}\mathrm{Ni} \qquad \Rightarrow$$

$$\Delta_{\mathrm{mass}} = 4 \times 1.0078u + 57.9353u - 61.9283u = 0.0379u$$

In the Lugano test the total fuel mass in given in the Report as 1g, and the fraction of Ni in the fuel as 55%. For a lower bound on expected energy we consider only the ^{58}Ni which constitutes, according to the Report, 67% of the total Ni. The mass of ^{58}Ni is therefore approximately 0.37g, and the mass loss is therefore:

$$\Delta_{\mathrm{mass}} = 0.37\frac{0.038}{58}g = 2.4 \times 10^{-7}\mathrm{kg} =$$

$$2.16 \times 10^{10}\mathrm{J}/c^2 = 6000\mathrm{kWh}/c^2$$

The total time of the test is stated in the Report as 32 days, or 768 hours, and therefore the expected average rate of excess heat would be 7.8kW. This is a total energy release some 20× larger than that possible given the observations allowing ±50% error. Therefore an additional extraordinary hypothesis would be required, of some endothermic nuclear reaction to balance the exothermic Ni conversion. Even then the Ni conversion remains anomalous because such complete conversion, implying reactant exhaustion, is not compatible with the constant power versus time dependence observed.

The Report concludes that the anomalous heat production, supported by this isotopic shift evidence, provides strong support for the hypothesis of a nuclear reaction. The isotopic shift remains a most extraordinary anomaly but it is one that hypothesized LENR does not resolve. It should be noted that this test is not independent. The device inventor conducted the fuel insertion and removal, and therefore was involved in the sample loading and sample collection process.

VIII. Conclusions

The Report [2] details a test of a new device with supposed extraordinary properties of sustained power generation with high energy and power density, that if true would be of great scientific and commercial significance. The suggested mechanism of low temperature nuclear reactions, capable of delivering the claimed high energy and power density, is supported by unusual isotopic shift measurements. These two measurements together, if correct, would be difficult to explain without some extraordinary mechanism.

The Report calculates a COP (power out / power in) of 3.2 and 3.6 for two tests with 755W and 865W input respectively. They suggest that the high calculated COP is evidence of large excess heat, and that this is further supported by the high differential COP: in this case 110W of extra input results in 761W of extra output.

The report uses an indirect method to calculate COP, and has neither control data, nor direct measurement of the device temperature.

The analysis here shows that the estimated excess heat in the Report is wrong, and results from an incorrect assumption that alumina is a gray body with temperature-dependent emissivity. In fact alumina has a non-gray-body frequency-dependent *spectral emissivity* that combines with Plank's Law to result in a temperature-dependent total emissivity. The infra-red thermography results must thus be adjusted using the relevant band emissivity of alumina, not the temperature-dependent total emissivity.

We show that when this error is corrected the resulting temperature is 779C, not the claimed 1401C. The total estimated power out from the system shows a COP of 1.07 and matches power in to within possible experimental error. Remarkably, the two tests with 755W and 865W input have very similar COP, and this similarity is not very sensitive to changes in parameters such as alumina emissivity. Thus the argument for high differential COP used by the Report as additional evidence falls and both the COP and differential COP are as expected for a system with no excess heat.

The code used to perform the recalculations is shown in Appendix A together with the precise data used to obtain the results quoted here. The potential errors in this experiment remain considerable and are discussed in Section VI above.

There are also some additional errors in the recalculation due to the incomplete data published on the Report, and the use of averaged reported temperatures. Nevertheless both the COP adjustment, and the differential COP adjustment, are robust.

The unusual isotopic shift between the reactor "fuel" and the "ash" remains unexplained. It should be noted that both insertion and removal of this material from the reactor was handled by the device inventor Rossi and therefore, although the isotopic analysis was conducted independently, this result does not constitute independent evidence.

It is interesting that the mistake made in the Report would have been immediately detected had the experimental methodology followed normal thermographic practice and controlled temperature measurement through an independent check of surface emissivity. Alternatively a control experiment using a device without fuel and equal power input to that used in the active tests, as is common practice, would test assumptions. Such practice would improve the quality of any future tests.

IX. Postword

An early draft of this paper was provided informally to the authors of the Report in order that they might refute any part of it that was wrong, or correct their mistake. It is unfortunate that the response has been silence, both publicly and privately. The mistake identified here invalidates the independent conclusion of the Report that Rossi's reactor generates abundant excess energy. It is therefore necessary, given that they do not refute this comment, that the authors of the Report retract this conclusion.

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Appendix A - Code

```
#---------------------------------------------------------------------------------
# Name:       Emissivity Calculations
# Purpose:    numerical integration of Planck Law
# Version:    1.2
# Python:     2.7
#---------------------------------------------------------------------------------
# Changelog:
# v1.1 -> v1.2
# add emissivity correction for reactor ridges.
# every real emissivity is corrected by e' = e/(1 - F(1-e))
# however note that the report emissivity is still used since it was entered
# into Optris without any correction for ridges and affects report results
# v1 -> v1.1
# Bolometer function added to calculation (instead of assuming constant
# in range 7.5u - 13u)
# Description added to power adjustment approximations
# Results printed for a range of possible inputs:
# band emissivity, bolometer characteristics.
# dummy run "ballpark figure" for temp explained and made weighted av of
# surface temps. NB this is still not done properly!

from math import exp,sin,pi
from functools import partial

import scipy.interpolate as sp
import numpy
import matplotlib.pyplot as plt

#Physical constants (SI units)
c = 2.997e8
k = 1.38e-23
h = 6.626e-34


NUM_PTS = 100 # number of points for numerical integration and interpolation
BANDL = 7.5e-6
BANDH = 14e-6

# Play with these constants to show sensitivity of results to emissivity
BAND_E_BIAS   = 1.0 # 1.0 => no change, multiples (1-e) spectral values in band
                    # e.g. 2 moves values up from 0.9 to 0.95, 0.8 to 0.9 etc
                    # e.g. 0.5 moves values down 0.9 to 0.8, 0.8 to 0.6 etc

REAL_E_BIAS    = 1.0 # 1.0 => no change, multiplies low e values

BOLOMETER_SKEW = '' # '' => normal, 'high' => high lambda bias,
                    #               'low' => low lambda bias


ROOM_TEMP = 21      #  Centigrade


data = {
# datasets from report: Temp/C, Pin, Prad, Pconv, Prods, Pjoule
# each item has as key the number of the relevant active run file or 0 for dummy
        12:[1401, 907, 2398, 428, 353, 42 ],
```

```
        3: [1256, 791, 1725, 385, 308, 36],
        0: [400, 486, 183, 133, 130, 7] #NB see note below
        }
# Note on dummy figures.
# The data for the dummy run is given in different form from the active runs
# with details of temoeratures from different segments. Rather than complicate
# the analysis we take a surface weighted average temperature here.
# Because convection is much
# more important in the dummy this average is more correct for the calculation
# of the adjustment factor than the max recator body figure.
# It should be noted that the dummy run recalculation is therefore more "hand
# waving than the active runs recalculation. A better job could be done by
# considering each part separately for the dummy run - maybe that would deal
# with the remaining difference between dummy and active runs.


# points defining curve of alumina spectral emissivity in IR band
# NB there is a small change in this curve with temperature which is ignored
alumina_spectral_e_pts = sorted({  7e-6:0.92, 8e-6:0.94, 10e-6:0.95, 11e-6:0.90,
        12e-6:0.52, 13e-6:0.53, 15.5e-6:0.28}.items())

# points defining spectral sensitivity of IR camera within its band
bol_sens_pts = sorted({7e-6:0.1, 7.5e-6:0.2, 8.2e-6:0.9,
                    8.7e-6:1.0,9.6e-6:0.92, 10.1e-6:0.96, 11e-6:0.85,12e-6:0.5,
                    13e-6:0.41 ,13.5e-6:0.31,14.2e-6:0.34 }.items())

def bolometer_sensitivity_pts():
    return [(l, 0.0 if (l < 10e-6 and BOLOMETER_SKEW=='high') or
                (l > 10e-6 and BOLOMETER_SKEW=='low')
                else x) for (l,x) in bol_sens_pts]

# points defining the total emissivity curve for alumina used in the report
# note this does not need to be correct, just what the report testers used
# NB temperatures are in C not K
rep_alumina_tot_e_pts = sorted({ 20:0.66, 200:0.7,350:0.79, 480:0.7, 900:0.48,
                                1250:0.41, 1510:0.4 }.items())


view_factor = 1.0 - sin(pi/4.0) # correct view factor for ridges


#-------------------------------------------------------------------------------
#                               UTILITY FUNCTIONS
# ------------------------------------------------------------------------------

def e_adjust(e):
    # adjust e by view factor
    return e / (1.0 - view_factor*(1.0-e))

def temp_to_k(tempc):
    return tempc+273

def frange(x, y, jump):
   while x < y:
      yield x
      x += jump
```

```
def weighted_av(a, b, yfun, wfun):
# form weighted av of yfun weighted by wfun over range a to b
    ysum = 0
    wsum = 0
    for  y in frange(a, b, (b-a)/NUM_PTS):
        w = wfun(y)
        wsum += w
        ysum += yfun(y)*w
    return float(ysum)/wsum



def interp(t1, pts):
    if t1 < pts[0][0] or t1 > pts[-1][0]:
        print 'out of range interpolation input',t1, pts
        raise
    for i, (temp, e) in enumerate(pts):
        if temp > t1:
            temp0,e0 = pts[i-1]
            frac = (t1-temp0)/float(temp-temp0)
            return frac*e+(1-frac)*e0

# subfunction used to generate point data
def fun_to_pts(a, b, fun):
    res = {}
    for x in frange(a,b,(b-a)/float(NUM_PTS)):
        res[x]=fun(x)
    return sorted(res.items())



#-------------------------------------------------------------------------------
#                   FUNCTIONS CALCULATED FROM DATA
# ------------------------------------------------------------------------------


def rep_alumina_tot_e_fun(tp):
    # not adjusted for ridges since Report did not do this
    return interp(tp,rep_alumina_tot_e_pts)


def real_alumina_tot_e_fun(tp):
    # not adjusted for ridges since Report did not do this
    e = rep_alumina_tot_e_fun(tp)
    if e < 0.65:
        e *= REAL_E_BIAS
        if e > 0.65: e = 0.65
        if e < 0: e = 0
    return e

def alumina_spectral_e_fun(l):
    # used only for alumina emissivity in bolometer bandwidth
    # adjusted for ridges
    return e_adjust(1-((1- interp(l, alumina_spectral_e_pts))*BAND_E_BIAS))

def band_sens_weighting_fun(tp, l):
    return interp(l, bolometer_sensitivity_pts())*planck(l,tp)
```

```
# NB this is a function used to generate points on curve.
# These are then interpolated.
def alumina_band_e_fun_temp(tp):
    return weighted_av(BANDL, BANDH, alumina_spectral_e_fun,
        partial(band_sens_weighting_fun, tp))

# Interpolates points generated from above function - for efficiency
def alumina_band_e_fun(tp):
    return interp(tp, alumina_band_e_pts)


# the ideal black body spectrum function from theory
# constant multiplier here is arbitrary
# tp is temperature in C
# l is wavelength in metres
# result is divided by 1e30 to keep numbers within double bounds.
def planck(l, tp):
    return 1/((1e6*l)**5*(exp(c*h/(l*k*temp_to_k(tp)))-1.0))

def planck_band_ratio(tp1, tp2):
    vals1 = [band_sens_weighting_fun(tp1,l)
        for l in frange(BANDL,BANDH,(BANDH-BANDL)/float(NUM_PTS))]
    vals2 = [band_sens_weighting_fun(tp2,l)
        for l in frange(BANDL,BANDH,(BANDH-BANDL)/float(NUM_PTS))]
    return sum(vals1)/sum(vals2)

def solve(tp):
    # iterate to get temperature solving eqn
    r_target = rep_alumina_tot_e_fun(tp)/alumina_band_e_fun(tp)
    t1 = tp
    while planck_band_ratio(t1,tp) > r_target:
        r_target = rep_alumina_tot_e_fun(tp)/alumina_band_e_fun(t1)
        t1 *= 0.95
    while planck_band_ratio(t1,tp) < r_target:
        t1 *= 1.01
    while planck_band_ratio(t1,tp) > r_target:
        t1 *= 0.999
    return t1

#-----------------------------------------------------------------------------
#                  DISPLAY FUNCTIONS (REQUIRES NUMPY, SCIPY, PYLAB)
# ----------------------------------------------------------------------------

def interp1(pts):
    xv = numpy.asarray([x for (x,y) in pts])
    yv = numpy.asarray([y for (x,y) in pts])
    xnew = numpy.linspace(pts[0][0], pts[-1][0], 100)
    tck = sp.splrep(xv, yv, s=0,k=1)
    ynew = sp.splev(xnew, tck,der=0)
    plt.plot(xnew, ynew)
    plt.title('Band Emissivity')
    plt.show()



#-----------------------------------------------------------------------------
#                                 MAIN CODE
```

```
# -----------------------------------------------------------------


def pconv(dats):
    [t1,pin, prad,pconv,prods,pjoule] = dats
    global BOLOMETER_SKEW, BAND_E_BIAS
    # print the results for normal, biassed low lambda,
    # biassed high lambda, bolometer sensitivity (bskew)
    # and for band emissivity (band_bias) shifted higher (0.5) AND LOWER (1.5)
    # from nominal
    for band_bias in [1.0, 1.5, 0.5]:
        for bskew in ['', 'low', 'high']:
            BOLOMETER_SKEW = bskew
            BAND_E_BIAS = band_bias
            if not bskew: bskew = 'none'
            t2 = solve(t1)
            # Note that solve(t1) finds the real temperature t2 for a given
            # reported temperature t1. We then calculate power adjustment
            # factors (arad,aconv) = power_adj(t1,t2) for the ratios of real
            # rad or conv powers to reported powers
            # We apply these factors to the report powers to find the real powers
            #
            #
            #
            # The problem is that not all the reactor is at the same temperature
            # Available data for power is given as radiation, convection, rods.
            # The joule heating is a very small correction to pin.
            # The reactor body is at the headline temperature, the caps are at a
            # lower temperature. The surface areas are:
            # body = 10*1.25*e-3 = 12.5e-3 m^2
            # caps = 6*1.67e-3 = 10e-3 m^2
            #
            # we adjust radiation and convection using the factor for the reactor
            # body which makes 55% of the surface area, nearly all of the
            # radiated power (because of the high temp dependence) and more than
            # half of the convected power. The caps power thus has the wrong
            # conversion factor applied: at a lower temperature the reduction
            # factor will be less. However for active tests this is a small
            # effect, because Prad dominates and the contribution here from caps
            # is small.
            #
            # Note the way the dummy headline temperature is given as a ballpark
            # figure between body and caps, weighted by area.
            #
            # For dummy test the caps contribution is larger than for Prad but
            # here the difference between the power_adj factors for the two
            # areas is small. Overall the error due to this approximation is
            # similarly small. A more accurate calculation could be done for
            # the dummy test where more data is available. However this is
            # very close for the active test powers because radiation depends
            # as T^4 and is nearly all from the reactor body.
            # See elsewhere for a fuller error analysis.
            #
            # The rods temperature varies. We average the rad and conv factors
            # for a rough estimate. Given the rods contribution is small
            # this will suffice. We use the adjustment factor from this average
            # temperature for all the rods power.
            pout1 = prad+pconv+prods
```

```
            ar,ac = power_adj(t1,t2)
            ar2,ac2 = power_adj(t1/2, solve(t1/2))
            pout2 = prad*ar+pconv*ac+prods*(ar2+ac2)/2
            print(
    "Bias=%4s,%3.1f:  %dC, %dC(real) Pin=%.1f, Pout=%.0f, Pout(real)=%.0f,"\
    "COP(real)=%.3f" % (bskew, band_bias, int(t1), int(t2), pin-pjoule, pout1,
                round(pout2), pout2/float(pin-pjoule)))


# returns pair of adjustment factors for radiation and convection
# for given report (t1) and real (t2) temps
# NB e is adjusted for ridge effect
def power_adj(t1, t2):
    # NB - this is not the right adjustment! it over-adjusts for ridges.
    # in reality e_adjust should be applied to spectral emissivity
    # of alumina and the results integrated weighted by the Plank Law
    # to get adjusted total emissivity.
    # still this is an OK approximation, better than no adjustment.
    prad_amb = e_adjust(real_alumina_tot_e_fun(ROOM_TEMP))*temp_to_k(ROOM_TEMP)**4
    a_rad = (e_adjust(real_alumina_tot_e_fun(t2))*temp_to_k(t2)**4 - prad_amb) / \
        (rep_alumina_tot_e_fun(t1)*temp_to_k(t1)**4-prad_amb)
    a_conv = ((t2-ROOM_TEMP)/(t1-ROOM_TEMP))**1.25
    return (a_rad,a_conv)



def main():
# This is a calculated set of points on the curve for the alumina effective
# band emissivity with temperature.
# This varies with temperature slightly due to different weighting by bolometer
# sensitivity and black body spectrum
    global alumina_band_e_pts
    alumina_band_e_pts = fun_to_pts(100, 1600, alumina_band_e_fun_temp)

# print the conversion data and compare with report data
    for (n,dats) in data.items():
        print n
        pconv(dats)
    print('e-adjust', 0.4, e_adjust(0.4), e_adjust(0.4)/0.4)
    interp1(alumina_band_e_pts)
    return




if __name__ == '__main__':
    main()
```